Economic Modelling of New Nuclear Power Plants

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ABSTRACT

In the 21st century the world faces a new challenge of drastically reducing emissions of greenhouse gases while simultaneously expanding energy access and economic opportunity to billions of people. Nuclear energy would seem to be ideally placed to meet that challenge.

Nuclear energy's future role, however, is highly uncertain for several reasons: primarily, escalating costs and, to a lesser extent, the persistence of historical challenges such as spent fuel disposal and concerns about nuclear plant safety and nuclear weapons proliferation.

Nuclear power plants are expensive to build but relatively cheap to run. In many places, nuclear energy is competitive with fossil fuels as a means of electricity generation. Waste disposal and decommissioning costs are usually fully included in the operating costs. If the social, health and environmental costs of fossil fuels are also taken into account, the competitiveness of nuclear power is improved.

The basic metric for any generating plant is the Levelised Cost of Electricity (LCOE). It is the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period, hence typically cost per megawatt hour.

This paper will describe the development and results of two economic models of new nuclear power plants using the most recent and relevant data available to the authors.

Keywords: *NPP costs estimates, LCOE, economic calculations, economic modelling*

1 INTRODUCTION

Harnessing the power of the atomic nucleus for peaceful purposes was one of the most astonishing scientific and technological achievements of the 20th century. It has benefitted medicine, security, and energy. Yet, after a few decades of rapid growth, investment in nuclear energy has stalled in many developed countries and nuclear energy now constitutes a meagre 5% of global primary energy production. [1]

Nuclear power can be an economic source of electricity generation, combining the advantages of safety, security, reliability, virtually zero greenhouse gas emissions and cost competitiveness. Existing plants function well with a high degree of predictability. The operating costs of these plants are usually very competitive, with a low risk of significant operating cost inflation, and the capacity factors of existing plants are high. **Error! Reference source not found.**

Financing a new nuclear power plant is challenging right from the beginning and the problem of very high capital costs during the construction phase is not the only one. Long planning periods with high risk capital as well as many political influences during a long decision and planning process are the factors that are complicating economic viability calculations. [3]

The authors of this paper developed two economic models of new nuclear power plants. Despite some shortcomings, the LCOE methodology was used, mainly because it remains a transparent consensus measure of generating costs and a widely used tool for comparing the costs of different power generating technologies in modelling and policy discussions. [4]

2 METHODOLOGY OF ECONOMIC CALCULATIONS

This chapter presents the levelised cost formula used to calculate lifetime (long-run) average levelised costs of new nuclear power plants, as well as definitions of certain project financial parameters – Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period.

2.1 Levelised Cost of Electricity (LCOE)

LCOE is a useful tool for comparing the unit costs of different technologies over their operating life. These costs are discounted to the commercial operation of an electricity generator. The LCOE methodology reflects generic technology risks, not specific project risks in specific markets. Given that such risks exist, there is a gap between the LCOE and the financial costs for owner-operators in real electricity markets facing specific uncertainties. For the same reason, LCOE is closer to the real cost of investment in electricity production in regulated monopoly electricity markets with regulated prices rather than to the real costs of generators in competitive markets with variable prices. Because of the many technical and structural determinants such as the non-storability of electricity, the variability of daily electricity demand or the seasonal variations in both electricity supply and demand, electricity prices, in particular spot prices, can be volatile where these are allowed to fluctuate. [4]

LCOE is a transparent consensus measure of generating costs and a widely used tool for comparing the costs of different power generating technologies in modelling and policy discussions. The calculation of the LCOE is based on the equivalence of the present value of the sum of discounted revenues and the present value of the sum of discounted costs. Another way of looking at LCOE is that it is the electricity tariff with which an investor would precisely break even on the project after paying debt and equity, after accounting for required rates of return to these investors. [4]

The decisive factor for the calculation of the LCOE is that all payment streams are assumed at either nominal or real levels. A mixture of real and nominal values is not permitted and will result in an error. Real cost inputs are used when calculating the LCOE as there is significant uncertainty regarding long term future inflation. For this reason, as part of this economic analysis, all costs are assumed to be in real terms and hence the discount rate (or WACC) used to calculate the LCOE must also be real. [Hendricks report NEK].

The LCOE formula used in this paper is as follows:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (1)$$

where the different variables indicate:
I_t = Total capital construction costs in year t;
M_t = Operation and maintenance costs in year t;
F_t = Fuel costs in year t;
$(1 + r)^t$ = The discount factor for year t (reflecting payments to capital);
E_t = The amount of electricity produced in MWh, assumed constant.

Some confusion could arise if equation (1) was taken out of context. In that equation, it looks as if MWhs are being discounted. Because LCOE is a constant, it can be taken out of the summation of revenues over the plant's lifetime and both sides of equation (1) can be divided by this summation. It is not the MWhs that are being discounted, it is the revenue from those MWhs that is being discounted. Revenue today has more value to the investor/owner/operator than revenue tomorrow. It is not output per se that is discounted, but its economic value. This is standard procedure in cost-benefit accounting. [4]

2.2 Net Present Value (NPV)

Long-term investment projects like Nuclear Power Plants are typically evaluated on the basis of Discounted-Cash-Flow (DCF) models, where the expected future revenues, costs and cash flows to the debt and equity capital providers are modelled and then discounted to the present based on the real cost of the debt capital and the return expected by the equity capital investors. The sum of the present values of the cash flows in the future is referred to as the Present Value (PV) of the project.

When deducting the investment cost from the PV we arrive at the Net Present Value (NPV) of the project. Projects with an NPV = 0 just about cover their cost of capital. Any positive NPV is also referred to as excess return (above the cost of capital) and accrues to the equity investors, who thus realize a return above the level expected/required by them. Needless to say, the higher the excess return the better, therefore investors are interested in maximizing NPV. [5]

NPV accounts for the time value of money and can be used to compare investment alternatives that are similar. It relies on a discount rate of return that may be derived from the cost of the capital required to make the investment, and any project or investment with a negative NPV should be avoided. An important drawback of using an NPV analysis is that it makes assumptions about future events that may not be reliable. [6]

The following formula is used to calculate NPV:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{2}$$

where:
R_t = Net cash inflow-outflows during a single period t
i = Discount rate or return that could be earned in alternative investments
t = Number of time periods

2.3 Internal Rate of Return (IRR)

The internal rate of return (IRR) is a metric used in capital budgeting to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the NPV of all cash flows from a particular project equal to zero. IRR calculations rely on the same formula as NPV does.

The following formula is used to calculate IRR:

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{3}$$

where:
C_t = Net cash inflow during the period t
C_0 = Total initial investment costs
IRR = The internal rate of return
t = Number of time periods

To calculate IRR using the formula, one would set NPV equal to zero and solve for the discount rate (r), which is the IRR. Because of the nature of the formula, however, IRR cannot be calculated analytically and must instead be calculated either through trial-and-error or using software programmed to calculate IRR.

Generally speaking, the higher a project's internal rate of return, the more desirable it is to undertake. IRR is uniform for investments of varying types and, as such, IRR can be used to rank multiple prospective projects on a relatively even basis. Assuming the costs of investment are equal among the various projects, the project with the highest IRR would probably be considered the best and be undertaken first.

IRR is sometimes referred to as "economic rate of return" or "discounted cash flow rate of return." The use of "internal" refers to the omission of external factors, such as the cost of capital or inflation, from the calculation.

While IRR is a very popular metric in estimating a project’s profitability, it can be misleading if used alone. Depending on the initial investment costs, a project may have a low IRR but a high NPV, meaning that while the pace at which the company sees returns on that project may be slow, the project may also be adding a great deal of overall value to the company.

A similar issue arises when using IRR to compare projects of different lengths. For example, a project of short duration may have a high IRR, making it appear to be an excellent investment, but may also have a low NPV. Conversely, a longer project may have a low IRR, earning returns slowly and steadily, but may add a large amount of value to the company over time. [7]

2.4 Payback Period

The payback period refers to the amount of time it takes to recover the cost of an investment. Simply put, the payback period is the length of time an investment reaches a breakeven point. The desirability of an investment is directly related to its payback period. Shorter paybacks mean more attractive investments.

The payback period is the cost of the investment divided by the annual cash flow. The shorter the payback, the more desirable the investment. However, it ignores the time value of money unlike other methods of capital budgeting such as NPV, IRR and discounted cash flow. The payback period does not account for what happens after payback, ignoring the overall profitability of an investment, but it can be used as an additional point of reference in a capital budgeting decision framework.

3 A BREAKDOWN OF NUCLEAR POWER PLANT COSTS

There are three basic components to the cost of a new power plant that produces electricity (or any other energy product), whether the plant uses nuclear technology or any other technology: capital cost, operating cost, and fuel. [1]

3.1 Capital costs

Capital costs are incurred while the generating plant is under construction and include expenditure on the necessary equipment, engineering and labour, as well as the cost of financing the investment. **Error! Reference source not found.**

The overnight cost is the capital cost exclusive of financing charges accruing during the construction period. The overnight cost includes engineering, procurement and construction (EPC) costs, owners' costs (land, cooling infrastructure, associated buildings, site works, switchyards, project management, licences, etc.) and various contingencies. **Error! Reference source not found.**

Construction/investment cost is the capital cost inclusive of all capital cost elements (overnight cost, cost escalation and financing charges). The construction cost is expressed in the same units as overnight cost and is useful for identifying the total cost of construction and for determining the effects of construction delays. In general, the construction costs of nuclear power plants are significantly higher than for coal- or gas-fired plants because of the need to use special materials, and to incorporate sophisticated safety features and backup control equipment. These contribute much of the nuclear generation cost, but once the plant is built the cost variables are minor. About 80% of the overnight cost relates to EPC costs, with about 70% of these consisting of direct costs (physical plant equipment with labour and materials to assemble them) and 30% indirect costs (supervisory engineering and support labour costs with some materials). The remaining 20% of the overnight cost is for contingencies and owners' costs (essentially the cost of testing systems and training staff). **Error! Reference source not found.**

Financing costs will be dictated by the construction period and the applicable interest charges on debt.

3.2 Operation and maintenance (O&M) costs

Operation and maintenance (O&M) costs may be divided into fixed costs, which are incurred whether or not the plant is generating electricity, and variable costs, which vary in relation to the output. Normally these costs are expressed relative to a unit of electricity (for example, cents per kilowatt hour) to allow a consistent comparison with other energy technologies. [2]

Decommissioning costs are usually included in the O&M costs.

3.3 Fuel costs

Low fuel costs have from the outset given nuclear energy an advantage compared with coal and gas-fired plants. Uranium, however, has to be processed, enriched and fabricated into fuel elements, accounting for about half of the total fuel cost. In the assessment of the economics of nuclear power, allowances must also be made for the management of radioactive used fuel and the ultimate disposal of this used fuel or the wastes separated from it. But even with these included, the total fuel costs of a nuclear power plant are typically about one-third to one-half of those for a coal-fired plant and between one-quarter and one-fifth of those for a gas combined-cycle plant. The US Nuclear Energy Institute suggests that the cost of fuel for a coal-fired plant is 78% of total costs, for a gas-fired plant the figure is 87%, and for nuclear the uranium is about 14% (or 34% if all front end and waste management costs are included).

Fuel costs are one area of steadily increasing efficiency and cost reduction. For instance, in Spain the cost of nuclear electricity was reduced by 29% over the period 1995-2001. Cost reductions of 40% were achieved by boosting enrichment levels and burn-up. Prospectively, a further 8% increase in burn-up will give another 5% reduction in fuel cost.

Uranium has the advantage of being a highly concentrated source of energy which is easily and cheaply transportable. The quantities needed are very much less than for coal or oil. One kilogram of natural uranium will yield about 20,000 times as much energy as the same amount of coal. It is therefore intrinsically a very portable and tradeable commodity.

The contribution of fuel to the overall cost of the electricity produced is relatively small, so even a large fuel price escalation will have relatively little effect. Uranium is abundant and widely available.

There are other possible savings. For example, if used fuel is reprocessed and the recovered plutonium and uranium is used in mixed oxide (MOX) fuel, more energy can be extracted. The costs of achieving this are large, but are offset by MOX fuel not needing enrichment and particularly by the smaller amount of high-level wastes produced at the end. Seven UO2 fuel assemblies give rise to one MOX assembly plus some vitrified high-level waste, resulting in only about 35% of the volume, mass and cost of disposal.

4 DESCRIPTION OF ECONOMIC MODELS AND KEY ASSUMPTIONS

The authors of this paper developed two economic models for construction of new nuclear power plants: one model is using in-house developed methodology and the other is based on a model developed by the Massachusetts Institute of Technology (MIT). Detailed descriptions of the developed models are given below.

4.1 In-house economic model

A standard nuclear power plant of 1000 MWe capacity was selected as a basis for both models. Duration of power plant construction was estimated as 8 years. The total investment was estimated in the amount of 6,034,000,000 euros. [2] That amount was distributed over the construction years as follows: 5% for year one, 5% for year two, 20% for year three, 20% for year four, 20% for year five, 10% for year six, 10% for year seven and 5% for year eight.

The LCOE was calculated as a sum of the net present value of the total investment and the net present value of operation and maintenance costs divided by the net present value of the generated electricity. The discount factor was selected as 6%.

$$LCOE = \frac{\text{NPV of the total investment} + \text{NPV of operation and maintenance costs}}{\text{NPV of the generated electricity}} \tag{4}$$

Yearly fixed operation and maintenance costs were taken as 103.31 *EUR/kW*, whereas variable operation and maintenance costs were taken as 2.37 EUR/MWh. Assumed future prices of electricity were given by our in-house experts.

The calculated result was *LCOE* = 57.07 EUR/MWh. Of course, recent political and consequently economic developments greatly influence this model, which will be taken into account in the conclusion part of this paper.

The IRR was calculated as 3.51%, and the payback period as 20 years.

4.2 MIT model

The LCOE pursuant to the MIT model is given by:

$$LCOE = \frac{1000}{8766 \cdot L} \cdot \left(\Phi \cdot \frac{I}{K} + \frac{O}{K} \right) + FCC \tag{5}$$

where:
K = power plant size [kWe];
L = annual capacity factor [actual kWhe/rated kWhe];
I = capital cost of the power plant including AFDC or IDC [EUR];
O = annual operating & maintenance cost [EUR/yr];
Φ= levelized fixed charge rate [yr^{-1}], accounting for both taxes and depreciation;
N = assumed plant economic life [years];
X= discount rate { $X = f_s r_s + f_b r_b (1 - \tau)$};
f_s = fraction debt;
f_b = fraction equity;
r_b = rate on debt (bonds) (%);
r_s = rate on equity (stock) (%);
τ = composite tax rate;
$1/N$ = straight-line depreciation fraction;
$(A/P,X,N)$ = Capital Recovery Factor = $[X(1 + X)^N]/[(1+ X)^N - 1]$;
FCC = fuel cycle cost;

and 8,766 is the number of hours in a year.

The nuclear fuel cycle cost is given by:

$$FCC = 1000 \cdot C_f / (24 \cdot \eta \cdot B) \quad (6)$$

where:

C_f = total [net] fuel cycle cost [EUR/kg], including enrichment, conversion, fabrication and disposal;

B = fuel burnup at discharge [MWD_{th}/MTU] [megawatt-days-thermal/ metric-ton-uranium]; and

η = plant thermal efficiency [kW_e/kW_{th}].

MIT cost estimates are based on traditional 'stick-built' construction in the United States for an 'nth-of-a-kind' (NOAK) plant. The NOAK plant is identical to the first-of-a-kind plant supplied and built by the same vendors and contractors with only the site-specific scope altered to meet the NOAK plant site's needs. Costs for NOAK plants are achieved only after many such reactors have been constructed for a particular nuclear system design. [1]

In the table below are the assumed cost inputs:

Table 1: Assumed cost inputs for a 1000 MWe new nuclear plant

Factor	Value
L = annual capacity factor, [actual kWh_e/rated kWh_e]	0,85
Φ= levelized fixed charge rate, [yr^{-1}]	0,10
I/K= specific capital cost, [EUR/kW_e]	5000
K = Plant capacity [MW_e]	1000
O/K= annual operating cost, [EUR/yr-kW_e]	70
C_f = total [net] fuel cycle cost [EUR/kg]	2500
B = fuel burnup at discharge [MWD_{th}/MTU]	50,000
η = plant thermal efficiency [kW_e/kW_{th}]	0.33
N = assumed plant economic life [years]	40

The result of the LCOE calculation is 67.72 EUR/MWh. If we were to take the total investment value of 6,034,000,000 euros as in our in-house model, the LCOE result would be 78.12 EUR/MWh.

5 CONCLUSION

The fundamental problem of nuclear power new build is cost. Other generation technologies have become cheaper in recent decades, while new nuclear plants have only become costlier. This disturbing trend undermines nuclear energy's potential contribution and increases the cost of achieving deep decarbonisation. [1]

This paper presented two economic models of new nuclear power plants using LCOE methodology. It is prepared to serve as a balanced, fact-based, and analysis-driven guide for stakeholders involved in nuclear energy.

LCOE methodology was used, a widely-used metric for comparing electricity generation costs, which howevever fails to adequately value the production of dispatchable, low-carbon power at the system level. Furthermore, this metric has shortcomings when it comes to evaluating system integration costs. The overall value of a given technology to the electricity system can only be understood when technologies are assessed together, not in isolation, but all of this surpasses the scope of this paper.

The LCOE results were 57.07 EUR/MWh for the in-house model and 67.72 EUR/MWh for the MIT model. Taking into account recent world developments, a large contingency should be added, but it is very difficult to assess what this amount should be.

There are several uncertainties surrounding economic models of new nuclear power plants. The first of these uncertainties is the possibility of a cost overrun. In that sense, some argue that the nuclear industry has an observed tendency to forecast overconfidence. There are also other significant uncertainties. The more critical are: construction durations, gas prices, carbon prices, and interest rates (including risk premiums for nuclear). Therefore, the final decision will have to be based on risk analysis, with many of the parameters difficult to fit in a probability distribution. This will probably require an analysis of the robustness of the decisions under an uncertain environment, which is outside the scope of this paper.

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